proceedings

Type of the Paper (Proceedings, Abstract, Extended Abstract, Editorial, etc.)

Digital polarization holography: challenges and opportunities

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Abstract: Polarization has a profound impact on image quality and visual perception. For instance, polarization provides a new perspective on seeing an object which is otherwise obscured, low contrast or not measurable by conventional imaging methods. In this paper, we discuss a possible extension of the digital holography (DH) to the polarization domain, and the technique is referred to as digital polarization holography (DPH). Basic principle of the DPH is described and some of our recent contributions on the quantitative vectorial imaging are covered. We also discuss and highlight potential of combining speckle field illumination with DPH for high-resolution vectorial imaging.

Keywords: Digital Holography, Polarization, Imaging

1. Introduction

Holography uses principle of interference to record and reconstruct the complex valued objects. Availability of high-quality detectors and computational facilities has popularized the holography through the digital holography (DH) where a hologram is digitally recorded and the reconstruction of the hologram is implemented by numerical methods [1]. The DH provides a quantitative information of the complex fields, i.e., amplitude and phase. This is advantageous in the context of real-time- live quantitative imaging, digital depth focusing, 3D, and label free-nondestructive imaging. Availability of array detectors and reconstruction algorithms have further revolutionized the holography. Different DH schemes have been developed, and significant among them are in-line, off-axis, and phase shifting holography. The off-axis holography requires angularly separated object and reference beams in the interferometric design, and this geometry avoids the twin image problem in the reconstruction. A concept of persevering information in the interference fringes has also been tested for self-luminous or incoherent object. Significant techniques among the incoherent holography are the coherence holography [2], and Fresnel incoherent correlation holography (FINCH) [3]. The coherence holography is an unconventional approach, wherein the complex valued object is reconstructed as a spatial distribution of the complex coherence function. In another development, DH methods are used to image 2D and 3D objects located behind the random scattering medium [4-6].

DH has emerged as a unique technique to quantitative measure wavefront of the light. A DH combined to the microscopy, called digital holographic microscopy (DHM) is nowadays widely used for wide range of applications [1]. However, a complete description of the wavefront needs inclusion of the polarization vector in the measurement, and analysis [7]. Polarization analysis is important in fields such as stress analysis, bio-medical imaging, chemistry and so on. Polarization states, a significant parameter to describe light matter interactions, have been critical and significant in the contrast enhancement and

Citation: To be added by editorial staff during production.

Academic Editor: Firstname Lastname

Published: date

highlighting specific cell structures which is otherwise missing in the scalar imaging. Therefore, polarization imaging is considered to be a promising and futuristic tool, as it is capable to reveal order at a molecular scale that is usually hidden to the conventional microscopes. Lohman was first to propose issue of total recording and reconstruction of the wavefront by including polarization vector in the wavefront reconstruction [7]. Extension of holography to the polarization domain is possible by recording and reconstruction of two holograms of the orthogonal polarization components [8-12]. In order to expand the polarization holography to the light with arbitrary coherence, it is desired to examine the interference in terms of the Stokes parameters of the light [9,10]. A practical challenge in the polarization holography is recording and reconstruction of four holograms corresponds to all four Stokes parameters. This issue has been attempted by using the random scattering as a real time recording plane and reconstructing the polarization vector by two-point complex correlations of the random light field. Polarization imaging of three-dimensional imaging using phase-shifting holography is also possible.

In this paper, we discuss polarization interference fringes and their role in recording and reconstruction of the complete wavefront. To demonstrate usefulness of the polarization fringes in the quantitative and spatially resolved imaging, beyond the conventional DH, we cover recording and reconstruction of the polarization holograms with a generic light source of variable correlations. We discuss different experimental designs of the digital polarization holography (DPH) and some of our recent contributions on the quantitative vectorial imaging. A new approach in the polarization domain of holograph, called speckle-field digital polarization holographic microscopy (SDPHM) is also discussed. The idea is to use a random pattern (rather than a uniform field) for illumination of the sample and thereby recover the high-resolution polarization features in comparison to the scalar DPH.

2. Polarization holograms

2.1. Digital polarization holography

Consider a recording geometry represented in Figure 1. This figure represents recording of a hologram by interference of the waves emerging from two sources, i.e. object and reference. Vectorial nature of the light waves, on the plane and vertical to the plane, are represented by a green arrow and black circle. Here, arrow represents the polarization vector on the plane and black circle represents a polarization vector perpendicular to this plane. Propagation of light field from the source to the observation is represented as

$$\boldsymbol{O_s(r) = \int O_s\,(\rho) G(r-\rho) d\rho} \quad (1)$$

$$\boldsymbol{R_s(r) = exp[i\alpha r]} \quad (2)$$

where $O_s(r)$ and $O_s(\rho)$ represent a realization of the object field at the observation and source plane, respectively and $s = x, y$ represents the orthogonal polarization components. $G(r-\rho)$ is propagation kernel to accommodate diffraction from the source position (ρ) to the spatial position (r) at the observation plane. A reference beam $R_s(r)$ is considered to be uniform with a linear phase of spatial frequency α.

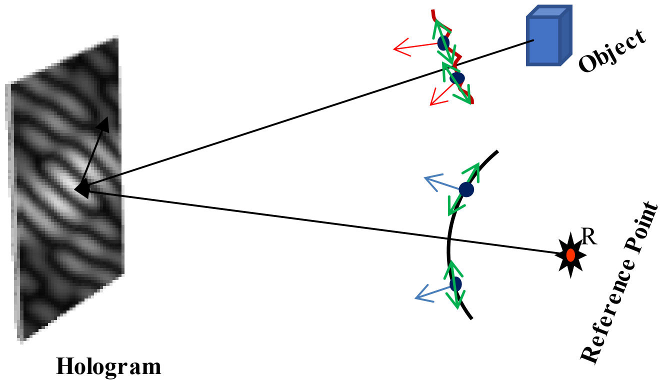

Figure 1. A schematic diagram to represent recording of hologram

2.2. Recording and reconstruction of polarization hologram

A single realization of orthogonally polarized components, at the observation plane, are represented as

$$\boldsymbol{E_x(r) = O_x(r) + R(r)} \quad (3)$$

$$\boldsymbol{E_y(r) = O_y(r) + R(r)} \quad (4)$$

Stokes fringes can be obtained from the orthogonal polarization components as

$$\boldsymbol{S_o(r) = \langle E_x^*(r)E_x(r)\rangle + \langle E_y^*(r)E_y(r)\rangle} \quad (5)$$

$$\boldsymbol{S_1(r) = \langle E_x^*(r)E_x(r)\rangle - \langle E_y^*(r)E_y(r)\rangle} \quad (6)$$

$$\boldsymbol{S_2(r) = \langle E_x^*(r)E_y(r)\rangle + \langle E_y^*(r)E_x(r)\rangle} \quad (7)$$

$$\boldsymbol{S_3(r) = i\left[\langle E_y^*(r)E_x(r)\rangle - \langle E_x^*(r)E_y(r)\rangle\right]} \quad (8)$$

where < . > angular bracket represents the ensemble average to evaluate the statistical properties of the light. Four Stokes parameters encode coherence-polarization features of the sources at the recording plane. First Stokes parameter in Eq. (5), i.e., $\mathbf{S_o(r)}$ represent the intensity and corresponds to the conventional hologram recording. Either a combination of $\mathbf{S_o(r)}$ and $\mathbf{S_1(r)}$ r or $\mathbf{S_2(r)}$ and $\mathbf{S_3(r)}$ is sufficient to reconstruct the full field of the object in a coherent recording. A detailed discussion on recording and reconstruction of the Stokes hologram can be found in Ref. [9,10].

3. Experimental design and implementation:

In order to consider a recording and reconstruction of holograms from the coherent and fully polarized source, we confine to the first two Stokes parameters and use holograms of the orthogonally polarized components, i.e.$I_{\mathbf{x}}(r) = |E_{\mathbf{x}}(r)|^2$ and $I_{\mathbf{y}}(r) = |E_{\mathbf{y}}(r)|^2$. An experimental scheme to simultaneously record these two holograms are shown in Figure 2. A specially designed Mach-Zehnder type polarization interferometer equipped with a triangular Sagnac geometry is used to simultaneously record the orthogonal polarization components. A collimated diagonally polarized coherent beam splits into two copies by a beam splitter (BS1). A beam, transmitted by BS1 and folded by the mirror M1, illuminates the sample. This object beam is imaged at the camera plane through the BS2. On the other hand, a beam reflected by the BS1 works enters into a triangular Sagnac interferometer assisted with a telescopic lens assembly (L2 and L3) to generate a distinguishable orthogonally polarized reference beam. A polarization beam splitter (PBS) splits into counter propagating orthogonally polarized components. The mirrors M2 and M2 introduce spatial separation in the orthogonally polarized components at the back focal plane of lens L2 which is also a front focal plane of lens L3. Thus, the orthogonally polarized components, coming out of the triangular Sagnac geometry, gain distinguishable linear phases at the back focal plane of lens L3 which overlaps with the detector plane. The angular multiplexed reference beams is a significant feature of our experimental design and this has been utilized for single shot polarization imaging [11] and Jones matrix microscopy [13] These reference beams interfere with the object beam and a hologram is recording by the charge coupled device (CCD). The intensity, recorded by the CCD, is represented as

$$I(r) = |O_x(r) + R_x(r)|^2 + \left|O_y(r) + R_y(r)\right|^2$$

where $R_x(r)$ and $R_y(r)$ are reference beams for x and y polarization components, respectively. Orthogonal polarization components of the object field are represented as $\boldsymbol{O_x(r)} = |\boldsymbol{O_x(r)}|\boldsymbol{e^{i\varphi_x(r)}}$ and $\boldsymbol{O_y(r)} = \left|\boldsymbol{O_y(r)}\right|\boldsymbol{e^{i\varphi_y(r)}}$.

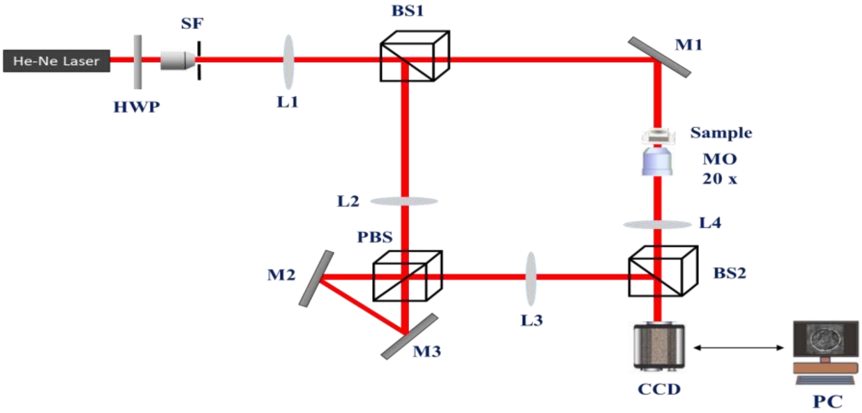

Figure 2. A schematic diagram to represent recording of hologram

For a demonstration purpose, we present an interference pattern of the biological object in Figure 2. A mesh structure in the interference pattern, as highlighted in the inset, appears due distinguishable carrier frequencies of the orthogonally polarized reference beams. This scheme is very important for recording and reconstruction of the spatially varying polarization of the object from a single hologram recording [11]. This recorded hologram is subjected to the digital Fourier fringe analysis to reconstruct the complex fields of the orthogonally polarized components, and results are shown in right hand side in Figure 3. Figure 3(a) represents the digitally recorded hologram. Figures 3(b) and 3(c) represent amplitude distributions of the orthogonal polarization components. Corresponding phase distributions are shown in Figures 3(d) and 3(e).

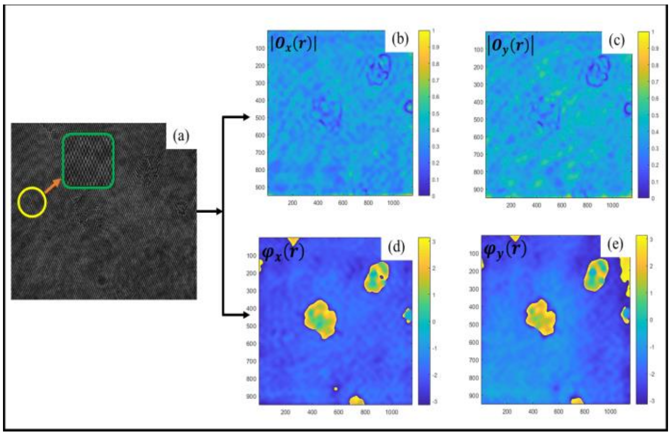

Figure 3. Reconstruction of compex fields of the orthogonal polarization components from a recorded hologram

4. Challenges and opportunities

In general, all four Stokes fringes are desired for a generic imaging application. An intensity fringe is one out of four Stokes fringes. Thus, recording and reconstruction of all four fringes may require multiple measurements by varying the polarization optics or using the polarization sensitive recording medium. A challenge of multiple step recording can be addressed by using polarization sensitive detector or using the random scattering medium as a real time recording medium with correlation-based reconstruction. Importance of the Stokes fringes in the polarization imaging can be highlighted by an example of interference between the orthogonal polarization components which is not possible by the conventional digital holography. Consider an off-axis object with a horizontally polarized transmittance, i.e., $\boldsymbol{O_x(\rho)} = |\boldsymbol{O_x(\rho)}|\boldsymbol{e^{i\varphi_x(\rho)}}$, and reference with a vertical polarization, i.e.,$\boldsymbol{R_y(\rho)} = \boldsymbol{1}$. Therefore, first two Stokes parameters at the recording plane, i.e.,$\boldsymbol{S_0(r)}$ and $\boldsymbol{S_1(r)}$, are made of only non-modulating terms and no interreference appears in these fringes as expected from the scalar theory. On the other hand, Stokes fringes $\boldsymbol{S_2(r)}$ and $\boldsymbol{S_3(r)}$ preserve a spatial carrier frequency introduced by the cross-modulations between the off-axis object and the on-axis reference source [10]. Recording and digital reconstruction of the polarization holograms have also offered new opportunity to use speckle field illumination for high resolution polarization imaging, and the technique is referred as speckle-field digital polarization holographic microscopy (SDPHM) [13]. A digital generated speckle pattern illumination in the SDPHM offers a new opportunity to explore high resolution polarization imaging.

5. Conclusion

Possible extension of the digital holography to the polarization domain is discussed and some of our recent contributions are briefly discussed in this paper. A special emphasis is given to the recording and reconstruction of a complete and spatially resolved polarimetric features from a single hologram.

Author Contributions: Rakesh Kumar Singh: preparation of the manuscript.

Funding: This work is supported by the Science and Engineering Research Board (SERB) India CORE/2019/000026 and the Department of Biotechnology (DBT) Grant No. BT/PR35587/MED/32/707/2019.

Conflicts of Interest: The authors declare no conflicts of interest.

Acknowledgments: This paper is based on research contributions of former and present lab members. R. K. Singh acknowledges support from the IIT (BHU) and different funding agencies

References

1. Schnars, U.; Jueptner, W. Digital Holography, 1st ed.; Springer: Verlag Berlin Heidelberg, Germany, 2005.
2. Takeda, M.; Wang, W.; Duan, Z.; Miyamoto, Y. Coherence holography. *Opt. express* **2005,** 13, 9629–9635.
3. Rosen, J.; Brooker, G. Digital spatially incoherent Fresnel holography. *Opt. Lett* **2007**, 32, 912-914.
4. Naik, D.N.; Singh, R.K.; Ezawa, T.; Miyamoto, Y.; Takeda, M. Photon correlation holography. *Opt. Express* **2010**, 19, 1408-1421.
5. Singh, R.K.; Vinu, R.V.; Sharma, A. Recovery of complex valued objects from two-point intensity correlation measurement. *Appl. Phys. Letter* **2014,** 104, 111108/1-4.
6. Singh, R.K.; Sharma, A.M.; Das, B. Quantitative phase contrast imaging through a scattering medium. *Opt. Lett.* **2014,** 39, 5045-5057.
7. Lohmann, A.W. Reconstruction of vectorial wavefronts. *Appl.Opt.* **1965**, 4, 1667-1668.
8. Colomb, T.; Dahlgren, P.; Beghuin, D.; Cuche, E.; Marquet, P.; Depeursinge, C. Polarization imaging by use of digital holography. *Appl. Opt.* **2002,** 41, 27-37.
9. Singh, R.K.; Naik, D.N.; Itou, H.; Miyamoto, Y.; Takeda, M. Stokes holography for recording and reconstructing objects using polarization fringes. *Proc. of SPIE* **2011**, 8082, 808209/1-10.
10. Singh, R.K.; Naik, D.N.; Itou, H.; Miyamoto, Y.; Takeda, M. Stokes holography. *Opt. Lett.* **2012**, 37, 966-968.
11. Sreelal, M.M.; Vinu, R.V.; Singh, R.K. Jones matrix microscopy from a single-shot intensity measurement. *Opt. Lett* **2017,** 42, 5194-5197.
12. Singh, D.; Singh, R.K. Lensless Stokes holography with the Hanbury Brown-Twiss approach. *Opt. Express* **2018**, 26, 10801-10812.
13. Vinu, R.V.; Chen, Z.; Pu, J.; Otani, Y.; Singh, R.K. Speckle-field polarization holographic microscopy. *Opt. Lett.* **2019,** 44, 5711-5714.

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